Costs, CO_2 emissions and energy balances of applying Nordic slash recovery methods in British Columbia

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Abstract

This paper evaluates the costs, CO_2 emissions and energy balances associated with three potential systems for recovering roadside slash in British Columbia, Canada, in which the biomass is transported as slash, hogfuel or bundles. Costs, CO_2 emissions and energy balances of all three systems showed strong dependence on transportation distance and considerably weaker dependence on slash amounts at landing (cutting block size). The results indicate that the hogfuel system is the cheapest, per unit delivered biomass, whereas the bundle system is the most expensive system when transportation distances are short (<100 km) and the slash system is the most expensive when transportation distances exceed 100 km. However, the viability of the systems is strongly dependent on payload assumptions.

Keywords: Bioenergy, supply-chain, logging residues, composite residue logs (CRL), biomass.

Introduction

Interest in the utilization of forest biomass for energy production has grown rapidly due to its potential to mitigate increases in greenhouse gases and reduce dependence on fossil fuels (e.g. Gan and Smith 2006, Aguilar and Garrett 2009, Galik et al. 2009). In British Columbia (BC), many communities are provided with hydroelectricity, while heat has been largely provided by the combustion of fossil fuels, mainly natural gas. Due to increased environmental concerns, the BC Government formulated an Energy Plan in 2002, the main objectives of which were to reduce fossil fuel consumption by increasing the contribution of renewable energy sources, including biomass (BC EMPR 2007). The abundance of suitable biomass in BC, especially biomass from trees damaged by mountain pine beetle (*Dendroctonus ponderosae*) infestation, has further increased interest in the utilization of biomass and the establishment of a substantial bioenergy industry.

In the conventional ground-based harvesting system utilized in BC, trees are cut by a feller-buncher and skidded from the block to the roadside without processing. At the roadside, trees are laid in supply piles for subsequent mechanical processing, often by a dangle head processor, which delimbs and tops trees and then places the processed logs in piles close to a road. The branches and tops are discarded in slash piles, approximately 10-13 meters from the centerline of the road (MacDonald 2006). To reduce fire hazards, slash piles are normally burned at the roadside as waste, thus increasing CO_2 emissions to the atmosphere. If the slash was recovered for energy purposes (e.g. combusted in combined heat and power stations), both electric power and heat could be produced in a manner that considerably reduced both the use of fossil fuels and CO_2 emissions (Jones et al. 2010). Ralevic and Layzell (2006) estimated the amount of biomass available from existing forestry operations in BC to be ca. 11.9 million raw tonnes per year, equivalent to ca. 53 TWh/yr. If the biomass in trees that is not suitable for lumber production due to mountain pine beetle infestation (approximately 960 million m^3 of woody biomass; Kumar et al. 2007) is also counted, the biomass available for energy purposes increases dramatically. Therefore, new proposals for using forest biomass (e.g. Verkerk et al. 2008) have been made, in addition to a few proposals from previous decades (e.g. Koch and McKenzie 1976). However, an expansion of slash utilization requires the establishment of both end-users and viable supply-chains.

The Nordic countries of Sweden and Finland are pioneers of the systematic large-scale use of forest residues for energy production (Hakkila and Parikka 2002, Junginger et al. 2005); limbs, tops and small non-commercial trees (i.e. slash in North America and logging residues in Europe) being the main assortment used. The dominant cut-to-length (CTL) method, with a bioenergy-adapted standard, results in piles of logs and slash in the harvested blocks. Indeed, after logs for lumber production and pulpwood for pulp production, slash is now the "third assortment" or "energy assortment". Various recovery systems for this new assortment have been developed in the Nordic countries (Andersson et al. 2002, Eriksson and Gustavsson 2010). However, slash is generally forwarded to roadside landing points and transported by trucks to industrial sites, where it is comminuted before combustion, although comminution may occur earlier in the supply-chain, either at landing or in-field. A less common alternative is to compress slash in-field into bundles (also called cylindrical bales or composite residue logs) using specially equipped forwarders. Bundles are then taken to the landing by normal forwarders and to industrial sites by trucks, where they are comminuted. Although bundling slash at roadside has been tested on a small-scale with both in-field machinery (Stampfer and Kanzian 2006, Spinelli and Magagnotti 2009) and machinery specially developed for this purpose (Lindroos et al. 2010), it is a rarely used recovery method. Hence, although different commercial logging systems are used in BC and the Nordic countries, slash is placed in roadside piles in both regions. In the Nordic countries, however, the roadside piles represent one category of the intended products of commercial harvesting (Andersson et al. 2002).

In slash recovery systems, the value of the recovered material is relatively low and the transportation techniques affect the delivered cost of material and consequently the profitability of the system (Ranta and Rinne 2006). Moreover, in attempts to reduce environmental impacts, the fuel consumption and the discharged CO_2 emissions are also crucial factors to consider in analyses of highly mechanized systems (e.g. Eriksson and Gustavsson 2010). Therefore, it is important to evaluate all possibly viable recovery systems thoroughly to identify the one that offers minimum costs and emissions. The potential for recovering in-field slash in Alberta and both pine beetle-infested trees and roadside slash in the interior of BC as feedstock for biomass power production has been analyzed in previous studies (Kumar et al. 2003, 2008, Mahmoudi et al. 2009). However, all of the previous studies assumed that only one recovery system would be used: comminution either in-field or at roadside. Hence, the province could benefit from evaluations of potential systems for recovering slash from roadside landings. Systems used for slash recovery in the Nordic countries could provide suitable benchmarks, but they would have to be adapted to suit the conditions in BC.

This study evaluates potential slash recovery systems in BC for utilizing forest biomass, which is a renewable resource and has the potential to mitigate increases in greenhouse gases. The emphasis is on comminution and road transportation activities during slash recovery. Estimates of costs, CO_2 emissions and energy balances of three systems, in which slash, hogfuel or bundles are transported, are presented. The results may be useful for companies that utilize comminuted woody biomass as a feedstock (e.g. woodpellet factories, power plants and thermal stations for district heating).

Methods and materials

The theoretical system analysis was mainly based on data in published literature, complemented with information obtained from field studies and contacts with both Swedish and Canadian companies and experts. Interviewed experts who supplied information are referred to as Swedish Experts or Canadian Experts, with the date they supplied the information, unless the expert concerned had agreed to being named. Due to space restrictions, only very limited justifications for the selected system components and other input variables can be presented. More detailed information is provided in Nilsson (2009).

Costs are expressed in Canadian dollars (C$) with 2008 as the base year. Consumer Price Indices and historical inflation rates (Bank of Canada 2008) have been used to adjust literature data to the base year.

Biomass features and amounts

In this study, it is assumed that most round-wood is recovered as sawlogs and pulp-wood by means of the ground-based harvesting system conventionally used in BC. In an attempt to reflect conditions in the interior of BC, the original stand volume was set to 250 m^3 per hectare, corresponding to 110 oven dry metric tonnes (ODt) per hectare (MacDonald 2006). Although it has often been assumed that slash constitutes 20% of the original biomass, in practice it has been found to range between 14 and 55% (MacDonald 2006). Therefore, we assumed that 30 ODt/ha (27%) of biomass was left as roadside slash after logging. The material's moisture content was set to 50% (wet weight) to reflect integration of recovery with the logging operation (i.e. it was assumed that slash would be stored for a negligible time). Given the small variation in calorific values for woody biomass, slash with the given moisture content was assumed to correspond to a net calorific value as received (lower heating value) of 4.74 MWh/Odt, based on an oven-dry net calorific value (higher heating value) of 5.41 MWh/ODt for whole trees of Scots pine (*Pinus sylvestris*) (Hakkila and Parikka 2002). In the study we analyzed slash recovery from cutting blocks of 5, 10 and 50 ha, with estimated total biomass amounts of 150, 300 and 1 500 Odt, respectively. The corresponding total energy in the cutting blocks was estimated to be 711, 1 422 and 7 110 MWh, respectively.

Selected systems

Three different systems in use in Sweden for recovering slash at roadside, and delivering it as hog fuel at the industrial yard were selected for evaluation (Fig. 1). In the Slash-system, unprocessed (loose) slash is transported by trucks to industrial sites, where it is comminuted into hog fuels (i.e. ground fractions). In the Hog fuel-system, comminution takes place at roadside landing, and trucks transport hog fuel to industrial sites. In the Bundle-system, slash is compressed at landing, and the resulting bundles are transported by trucks to industrial sites where they are comminuted into hog fuel.

Machinery

Trucks and speed

The common pole trailer truck was considered unsuitable for transporting bundles (MacDonald 2008, pers. com.). Instead, it was assumed that a 7-axle short-log truck combination with covered sides and bottom, equipped with a crane, would be used in all systems (Amlin 2008, pers. com.). The vehicle was assumed to have a load volume of 141 m^3, an empty mass of 18 t and a maximum payload of 42 t. When transporting hog fuel, it was assumed that trucks would unload to the side. Truck loads for hogfuel were set to 14.7 Odt, based on practical experience of operations in interior BC (Barbosa 2008, pers. comm.) and estimated to be 11.3 Odt for loose slash and 14.2 Odt for bundles (33 bundles).

Mean travel speeds were set to 45.6, 52.9, 56.2, 58.1, 59.5 and 60.3 km/h for transportation distances (hereafter 'distances', for convenience) of 50 to 300 km with 50 km intervals (MacDonald 2006). The speed was assumed to be higher for longer distances, since it was assumed that higher proportions of the journeys would be on fast roads, but no adjustment was made to account for possible differences in the speeds of loaded and empty trucks.

When being loaded and unloaded, the trucks were waiting, thus adding to the cost of the system. Time required for the operation was estimated from the loading/unloading machinery's productivity. The hourly cost of trucks was used in the cost calculations, but in CO_2 and energy calculations the fuel consumption when they were being loaded or unloaded (thus when the engine was idling) was set to 10% of the consumption during work.

Grinder

The grinder model assumed to be used in all three systems was the CBI Magnum Force 6800 horizontal grinder, with modifications for work at roadside or at the industrial yard. The grinders' productivity is 91 Odt/h (CBI 2008) in ideal conditions, but is limited in practice by the feeding capacity of the grapple loader, rather than the actual grinder (cf. Table 2). In stationary application the feeding rate in relation to possible grinding capacity (utilization rate) was used to estimate the energy inputs from the electric motors (utilization rate × 750 kW). The hourly required energy input was, hence, set to 108.4 kWh for loose slash and 255.5 kWh for bundles.

Bundler

The assumed bundler was the Swedish prototype Rogbico GTK 4800 (Rogbico AB, Sweden) with a bundling component mounted on a Scania 580 truck (Scania AB, Sweden) and a crane to feed and unload the batch-type compressing chamber. When processing slash of predominantly Norway spruce (*Picea abies*), the machine makes bundles that are 4.8 m long, with a diameter of 0.8 m and a mass of 0.39 Otd (Lindroos et al. 2010). To compensate for the assumed higher stemwood content (cf. MacDonald 2006) in the application considered here, bundle mass was increased by 10% and was assumed to have a mass of 0.43 Odt. The assumed productivity was 17 bundles per hour. Based on Swedish cost estimations (Edman 2009), the working costs were set to 200 C$ and allocation costs to 150 C$. Information on fuel consumption was not available, but based on truck fuel consumption it was assumed to be 30 l/h when compressing and 24 l/h when the truck was relocating.

Loaders

Swedish grapple loader productivity data (Näslund 2006, Eriksson 2008, Edman 2009) were considered reasonable under the proposed BC conditions, but values were increased by 10% to account for the higher expected stemwood content and basic density of the material. Grinder feeding at industrial sites was assumed to be 30% more productive than feeding at landing, due to larger slash concentrations and the structured environment. Only one grapple loader was set to feed the grinder since space was expected to be restricted, especially at landing.

Although a wheel-loader might be used to assist other slash-recovery machinery, only its loading of hogfuels on trucks was accounted for here. It was assumed to take 20 minutes to load a hogfuel-truck, which is equivalent to 44.1 Odt/h.

Relocations

For the bundler relocations, the hourly cost and fuel consumption were assumed to be 20% lower than for the bundling work, since the engine was assumed to produce 20% less power. The costs of grinder allocation consisted of the costs for the lowbed trailer and the grinder. The grinder's hourly costs during transport were assumed to be 33% cheaper than when in operation, because of the absence of operational costs. The time consuming elements in grinder relocations comprised pre-arrangements, installation and transport arrangements, which were each assumed to take approximately 0.5 hours (Heinrichs 2008, pers.comm.). Each transport was assumed to be a roundtrip (two-way distance), for which the time consumed was a function of distance and speed.

Models

The total cost per Odt at landing was modeled for each system by summing the cost of the included machinery according to Eqs. 1-3 for each system, i.e. the Slash-system ($C_{Tot(SL)}$), the Hogfuel-system ($C_{Tot(HF)}$) and the Bundle-system ($C_{Tot(B)}$), as follows:

$$C_{Tot(SL)} = C_{GL,loading} + C_{T,\ loading} + C_{T,\ transport} + C_{T,\ unloading} + C_{GL,unloading} + C_{GL,feeding} + C_{GR} \qquad \text{(C\$/ODt)} \qquad [1]$$

$$C_{Tot(HF)} = C_{R(GR)} + C_{GL,feeding} + C_{GR} + C_{W} + C_{T,\ loading} + C_{T,\ transport} + C_{T,\ unload} \qquad \text{(C\$/ ODt)} \qquad [2]$$

$$C_{Tot(B)} = C_{R(B)} + C_{B} + C_{GL,loading} + C_{T,\ loading} + C_{T,\ transport} + C_{T,\ unloading} + C_{GL,unloading} + C_{GL,feeding} + C_{GR} \qquad \text{(C\$/ ODt)} \qquad [3]$$

In these equations: C_{GL} is the cost of the grapple loader when feeding the grinder and both loading and unloading trucks; C_T is the cost of road transport with trucks and the costs when they are loaded and unloaded; C_{GR} is the costs of the grinder; $C_{R(GR)}$ and $C_{R(B)}$ are the costs of relocating the grinder and the bundler, respectively, to the landing and back; C_W is the cost of the wheel loader and C_B is the cost of the bundler. C_{GL}, C_{GR}, C_W and C_B were calculated according to Eq. 4, where *c* is the cost per hour for machine type *i* and *t* is the time consumed for the work performed (hours/Odt).

$$C_i = c_i \times t_i \qquad \text{(C\$/Odt)} \qquad [4]$$

C_T was calculated according to Eq.5, where m_T is the payload of the truck in Odt for the given material (Table 3) and t_T is the time consumed (in hours) in a roundtrip. The calculations account for the exact amount of slash that would be transported (e.g. 4.2 trucks rather than the five trucks that would actually be needed) in order to pinpoint systemic differences.

$$C_T = \frac{t_T}{m_T} \times c_T \qquad \text{(C\$/Odt)} \qquad [5]$$

$C_{A(GR)}$ was calculated according to Eq. 6, where $c_{A(GR)}$ is the grinder's cost per hour when transported, $c_{T(GR)}$ is the truck and lowbed trailer's cost per hour, t_A is the time consumed for relocation (hours) and *M* is the slash amount at landing (Odt). $C_{A(B)}$ was calculated essentially according to Eq. 4, but including the hourly cost of relocating the bundler (Table 1) and time consumption for a roundtrip of the given distance.

$$C_{A(GR)} = \frac{t_A\left(c_{A(GR)} + c_{T(GR)}\right)}{M} \qquad \text{(C\$/Odt)} \qquad [6]$$

All data on productivity in this study were calculated on the basis of Odt productive per work hour (PWh), with down time excluded. Hence, it is assumed that all systems have the same proportion of down time

Costs, fuel consumption and CO_2 emissions

All the used machinery was assumed to be owned by contractors and to be leased at an hourly rate (Table 1) that differed between relocations or productive work. The grapple loaders and wheel loaders were considered to be already on-site, as they were assumed to have been used in the preceding final felling.

The cost of one liter of diesel was set to 1.4 C$ and its energy content was set to 0.0107 MWh/liter (US EIA 2010). It was assumed that consumption of each liter of diesel resulted in 2.67 kg of CO_2 emissions to the atmosphere (US EPA 2005). As one of many greenhouse gases causing climate change, CO_2 was considered a relevant gas emission indicator in this study.

Results

As shown in Figure 2, costs, CO_2 emissions and energy balance of all three systems show a strong dependence on distance and a considerably weaker dependence on slash amounts at landing (cutting block size). At the smallest cutting block size, the costs per handled unit (in Odt or MWh) for all systems were quite similar, and the differences between them decreased with increasing distance. The cost per unit delivered biomass was lowest for the Hogfuel system, the Bundle system was the most expensive for short distances (<100 km) and the Slash system was the most expensive for long distances (>100 km).

There were also similarities between slash recovery systems in terms of CO_2 emissions and energy balance. For short distances (<10 km) the Slash system was the most favorable, but for longer distances, it generated the highest CO_2 emissions and used the most energy per recovered energy unit. Moreover, the differences in these respects increased with increases in the slash amounts. In this comparison, the Bundle system and the Hog fuel system were similar in terms CO_2 emissions and energy balance.

We also excluded transportation and the associated loading and unloading in order to analyze solely the comminution options. The results (Fig. 2, distance 0 km) indicate that comminuting loose slash with a stationary grinder in the Slash system is the most favorable system in terms of costs, CO_2 emissions and energy balance, while bundling slash before comminuting it in a stationary grinder is the least cost-efficient option. However, bundling before comminution was second best in terms of CO_2 emissions, and as favorable as comminuting loose slash in the stationary grinder in terms of energy balance.

When the payload of the trucks used in the Slash system was increased by 10%, without changing the truck payloads of the other systems, the system became cheaper or matched the costs of the bundle system for all assessed distances and slash amounts (data not shown). Moreover, it becomes equivalent to the Hogfuel system when there are small slash amounts and short distances, and the most viable system at longer distances (>150 km). It also tallies with other systems in terms of CO_2 emissions and energy balance at the assessed distances. A 10% reduction in payload makes the slash system considerably more costly than the other systems at distances longer than 100 km. When the payload of the trucks used in the Bundle system is increased by 10%, the system becomes the most cost-efficient for small slash amounts and long distances (>200 km). Moreover, it generally becomes the most efficient system in terms of CO_2 emissions and energy balance, with an increased advantage over other systems with increased distance. A decrease in payload by 10% makes the bundle system very similar to the slash system in terms of costs, CO_2 emissions and energy balance. A 10% increase in the payload of the trucks used in the Hogfuel systems makes the system the most viable in terms of costs, CO_2 emissions and energy balance for all distances except the very shortest (50 km). A 10% decrease in payload does not affect the reported cost relations, but the system becomes the least viable in terms of CO_2 emissions and energy balance. Simultaneously changing payloads for all systems equally (±10%) did not affect the relationships between systems.

Discussion and conclusion

Viability of the systems and practical adaptations

If transport distances are short, the total cost per unit transported and comminuted by a given system is mainly dependent on the cost efficiency of comminution, while for longer distances the truckload capacity and the relocation costs are the strongest determinants of competitiveness. Both transport and relocation costs increase with the distance. However, whereas the transport costs are independent of the amount of slash at landing, they are dependent on the density of the material; the higher the payload, the longer the possible transport at a given unit cost. The relocation costs per unit slash, on the other hand, decrease with increases in slash amounts, although the decrease declines considerably even at quite small slash amounts.

Given these general relationships, the finding that the Slash-system is competitive only for very small landings and very short transport distances is consistent with both expectations and previous studies (e.g. Ranta and Rinne 2006, Engblom 2007). With longer distances and larger slash quantities to distribute relocation costs over, it is worthwhile to process the material to increase transport payloads. Indeed, our estimates indicate that processing by comminution (as in the Hogfuel system) would be cost-efficient under the examined conditions with cutting blocks as small as 5 ha and a transport distance of ≥50 km (Hog fuel system).

The Hogfuel system's high relocation costs make it lose competitiveness with distance if slash quantities are small, but its competitiveness increases with distance when slash quantities are large. To exploit fully the benefits of using the highly productive grinder, large amounts of slash and efficient feeding are required. Thus, a large grinder is probably more suitable as a stationary unit at an industrial site or a terminal. If a mobile chipper is used instead, the fuel consumption, CO_2 emissions and costs of the comminuting and relocation are all likely to be lower, as chippers are normally smaller machines of lower productivity. Moreover, follow-up studies of chipped slash have indicated that it allows substantially higher truck payloads (ca. 17 ODt; Ranta and Rinne 2006) than the hogfuel payloads assumed in this study. However, chippers are more sensitive to dirty material than crushers. Irrespective of the comminution technique, a practical limitation of the assumed Hogfuel-system is that comminution at landing requires flat, cleared storage sites. An alternative to the study assumptions, if space allows, is to discharge comminuted material directly into a waiting truck, but then the comminution and road transport operations would be dependent on each other.

Because of the low relocation costs, the bundling system was as cost-efficient as the Hogfuel system for recovering small slash quantities with long distances, but the difference increased with larger slash quantities. However, irrespective of slash quantities and distances, the bundler system was equally viable in terms of CO_2 emissions and energy balance as the Hogfuel system. If the bundler was enhanced in line with the improvements suggested by Lindroos et al. (2010), the viability of the Bundle-system might increase considerably. However, with its differences in characteristics, the possibility of bundling BC slash using the Nordic technique warrants further investigation (cf. MacDonald 2006 for BC slash features and Johansson et al. 2006 for limitations in bundling of Nordic slash).

The costs estimated in the present study were almost twice as high as estimates in a previous theoretical study (ca. 45 C$/ODt; Mahmoudi et al. 2009), in which it was assumed that a considerably cheaper mobile chipper, discharging directly onto trucks, would be used for roadside comminution. However, estimated Swedish costs of recovering slash from the roadside, derived from data presented by Engblom (2007), are considerably higher than those obtained in the current study: 116 C$/Odt for a Slash-system and 106 C$/Odt for a Chipping-system (i.e. comminution with a chipper instead of a grinder) with a transport distance of 100 km (assuming an exchange rate of 1 C$ = 6.04 SEK; Bank of Canada 2008). Corresponding costs of 77 C$/Odt for a Slash system and 84 C$/Odt for a Bundle system were estimated by Lindroos et al. (2010), which tally with the costs in the study presented here, despite excluding relocation costs. However, besides possible differences in assumptions, cross-continent comparisons are also complicated by exchange rate fluctuations. Moreover, the Swedish costs are the result of several decades of efficiency improvement and accompanying cost-cutting (Junginger et al. 2005); this implies that a slash recovery system in BC is likely, initially, to have substantially higher costs. However, with the experiences from, for instance, the Nordic countries it should be possible to reduce greatly the learning phase.

Even though profitability was not targeted in this study, a comparison with Swedish conditions gives some valuable indications of viability. With a transport distance of 100 km, the total recovery costs (including slash forwarding) corresponded to ca. 80% of the price for comminuted biomass delivered to industrial sites (Swedish Experts 2008). To maintain the same cost–income relationship for slash recovery operations in BC, the required price would have to be at least 75 C$/Odt (16 C$/MWh) according to the cost levels in our study.

Benefits and limitations of the study

Given the constraints of this study, which evaluates systems that not yet are in operation, there are several unavoidable sources of possible variability and even inaccuracy. These include, for instance, the assumptions of solid content in roadside piles and trucks, the costs of machines, fuel consumption and machine productivity. The difficulties involved in transferring machinery costs and productivity from one region to another are due to several fundamental differences influencing their performance, such as landscape characteristics, infrastructure and laws. However, the study was based on the best available data in the literature and information from interviews with experienced stakeholders and researchers. Due to the inevitable study constraints, the absolute cost levels might prove to deviate from those in practical trials in BC. Nevertheless, this study should provide good indications of the relationships between cost and emission levels of each system and the effects of slash amount at landing and transport distance on their competitiveness.

The study has only addressed a limited part of a full life-cycle assessment of the systems in terms of energy and CO_2 efficiency. Assessments could be enhanced with, for instance, details of the value of replacing fossil fuels with slash, as was done by Jones et al. (2010), but at this early stage it was considered more relevant to focus on comparing the direct impact of several potential slash recovery systems.

End-user applications and future work

Naturally, to make recovery of slash meaningful there has to be an end-use for the biomass. In the Nordic countries, most slash is used for district heating and to some extent for energy in combined heat and power stations. It normally also constitutes part of a diversified feed-stock. Hence, replacing fossil fuel-based heating and expanding the district heating system in BC would probably accelerate the use of slash. However, before making such changes in infrastructure, it is important to assess the amount and cost of available feedstock. Mahmoudi et al. (2009), for instance, estimated that roadside slash could provide about a third of the feedstock required for a potential power plant in Quesnel, BC. Thus, the end-use and supply chain should ideally be jointly developed.

Industries and thermal power stations are often located close to a community, for obvious reasons, thus available land for storage and comminution can be limited. Further urbanization and competition for valuable land may therefore promote use of compressed biomass, i.e. disfavor the use of loose slash unless terminals are used.

With the Hogfuel-system end-users do not need comminuting capacity, which would reduce space requirements. The system also delivers a feedstock that cannot be stored for long periods due to deterioration of the biomass (Nurmi 1999), which might be well combined with limited space requirements (i.e. rapid consumption of small stock volumes). On the other hand, low stock makes end-users vulnerable to supply chain disturbances.

Bundles represent a compromise between loose and comminuted slash, because they are less bulky than loose slash and allow longer storage than comminuted material (Jirjis and Nordén 2005, Pettersson and Nordfjell 2007). Moreover, a standard unit is created that can be efficiently handled, thus giving logistic advantages. Consequently, the use of bundles makes it possible to keep relatively large stocks in limited areas, but require end-user comminution capacity.

As a next step in the assessment and, ideally, the establishment of viable slash recovery systems in BC, it is recommended that further studies should be directed towards theoretical evaluations of slash recovery systems with (a) specific location(s) of end-user(s). In such a set-up the conditions can be better defined and available slash quantities and characteristics, transportation costs and end-product quality can be assessed more thoroughly.

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Tables and Figures

Table 1. Machinery cost rates, fuel consumption and CO_2 emissions used in the analyses

Machinery	Used in system[a]	Hourly cost (C$/h)	Fuel consumption (l/h)	CO_2 emissions (kg/h) [b]
Grapple loader	S, H, B	104[1]	26[1]	69.4
Trucks	S, H, B	135[2]	40[2,c]	106.8
Stationary grinder	S, B	300[3]	0[d]	0[d]
Relocation of mobile grinder	H	470[3,b]	40[2]	106.8
Mobile grinder	H	500[3]	170[3]	453.9
Wheel loader	H	110[1]	20[1]	53.4
Relocation of bundler	B	150[4]	24[5]	64.1
Bundler	B	200[4]	30[5]	80.1

[a] S= Slash system; H = Hogfuel system; B = Bundling system.

[b] Based on fuel consumption and 2.67 kg of CO_2 emissions per liter diesel (US EPA 2005).

[c] When being loaded and unloaded (and the engine was idling), fuel consumption was set to 10% of work consumption.

[d] Powered by electricity, which was assumed to be generated in a CO_2-neutral manner.

[e] Hourly rates for the grinder and for the truck transporting the grinder on a lowbed trailer, assumed to be 335 C$ and 135 C$, respectively.

Superscript numbers indicate data sources: [1)] MacDonald 2006, [2)] MacDonald 2008, [3)] Heinrich 2008, [4)] Edman 2009, [5)] estimates based on truck fuel consumption and Edman 2009.

Table 2. Grapple loader productivity in the considered operations with the indicated materials

Operation	Material	Odt/h
Loading truck	Slash	14.3[a]
	Bundles	43.5[b]
Unloading truck	Slash	39.6[a]
	Bundles	58.1[b]
Feeding grinder	Slash at landing	32.4[c]
	Slash at industry	42.1[c]
	Bundles	81.3[b]

Data derived from [a)] Näslund 2006, [b)] Edman 2009 08 and [c)] Eriksson 2008.

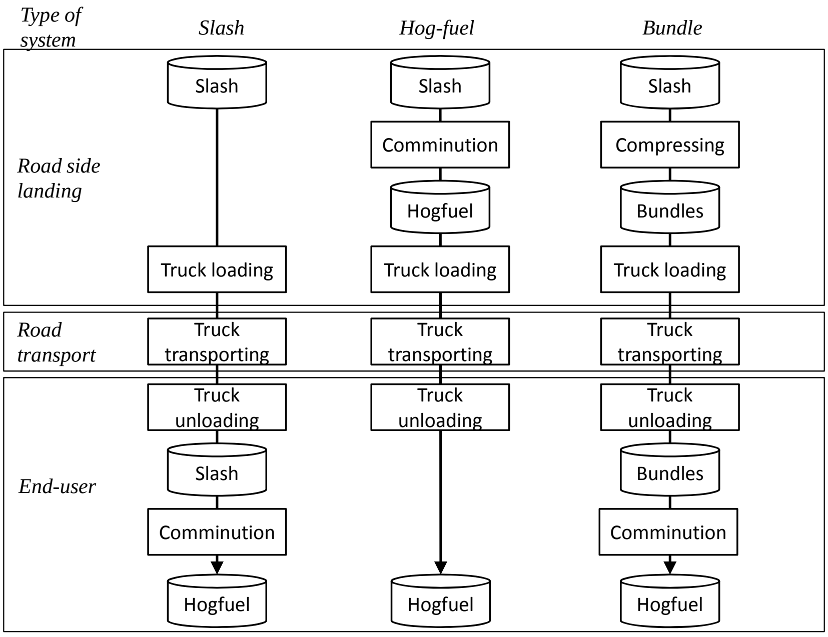

Figure 1. Flow chart for the three evaluated slash-recovery systems and their main processes. Cylinders indicate biomass storage points and rectangles indicate processing points.

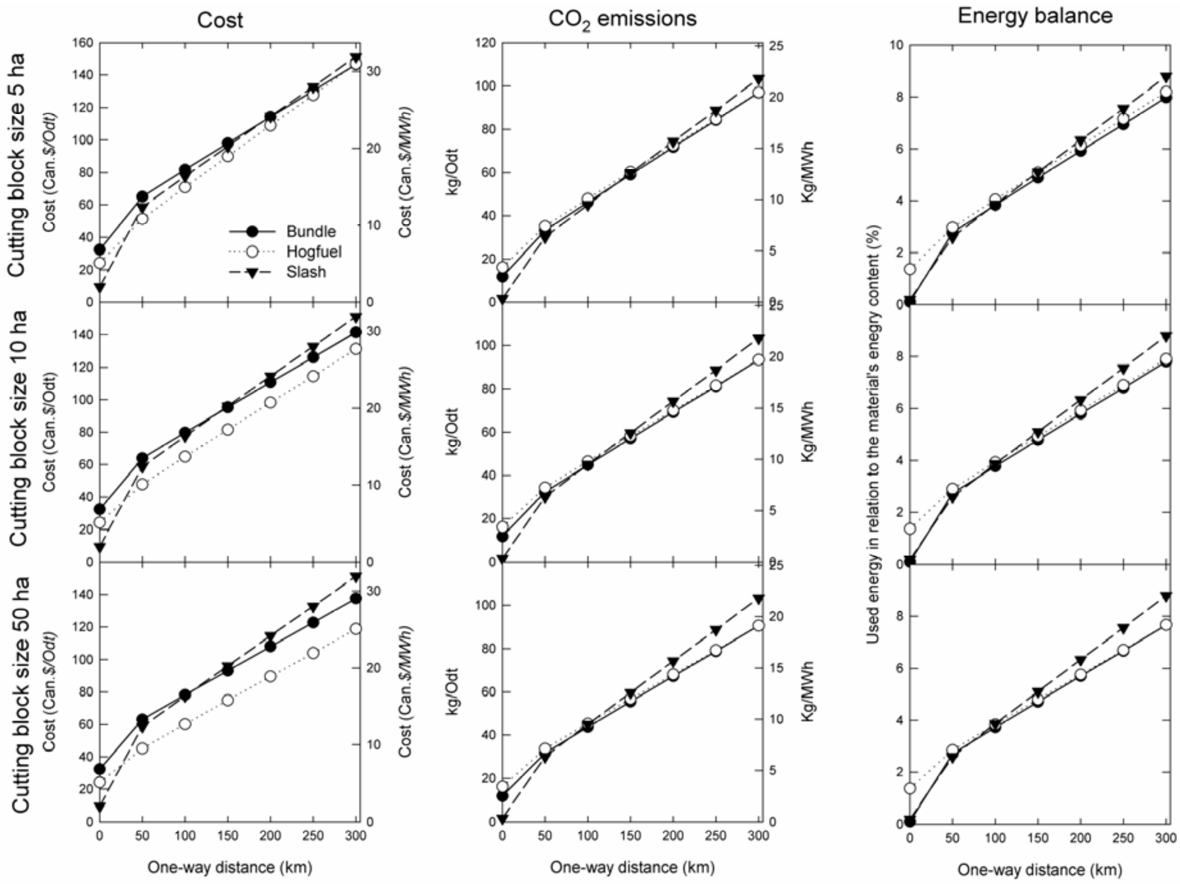

Figure 2. Costs, CO_2 emissions and energy balances of the slash recovery systems for the indicated slash amounts at landing (cutting block sizes) as a function of transport distances.